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THE POTENTIAL FOR REDUCING CARBON EMISSIONS FROM INCREASED EFFICIENCY: A GENERAL EQUILIBRIUM METHODOLOGY

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May 18, 1990

THE POTENTIAL FOR REDUCING CARBON EMISSIONS FROM INCREASED EFFICIENCY: A GENERAL EQUILIBRIUM METHODOLOGY

I. Introduction

One approach to reduction of carbon emissions that has often been suggested is through an increase in the efficiency of use of hydrocarbon fuels, i.e., achieving more output for the same amount or lesser fuel input. It seems like an obviously desirable prescription, particularly if it can be done with just a little improvement in technique and tuning. Something for nothing is always a good trade.

The argument has been generalized, however, to situations in which better fuel efficiency requires more of other inputs, including, usually, capital. But, in this case, the prescription becomes less obviously a good one. What if the costs of production go up? What if production of the capital and/or the other inputs is, itself, relatively fuel intensive? As is often the case, a closer look reveals complexities that were not so obvious at first glance.

This paper presents a methodology for analyzing the potential for reduction in carbon emissions through increased fuel efficiency and provides an illustration of the method.[1] It is intended as a demonstration of technique rather than a substantive

contribution, although it may help illustrate the general structure of possibilities.

The methodology employed is a multisectoral, intertemporal, programming model embodying significant non-linearities in production and consumption. The demonstration uses a model that was first constructed to analyze energy policy in Egypt. It is, therefore, a special case, representing a developing country that utilizes only two hydrocarbon fuels, natural gas and petroleum, with only a negligibly small amount of imported coal.

The results should be considered only as illustrative for other reasons as well. First, while the basic parameters were estimated from existing data for the Egyptian economy, the numbers used for the alternative, more fuel efficient technologies are point estimates made by the authors. It adds only a modest amount of credence to them to say that our conjectures were based on our reading of the available literature.[2]

Second, it is assumed that the constraints on carbon emissions, that are used to illustrate the potential, can be effectively enforced. Conceivably that could be done by direct regulation or through the use of taxes as indicated by the shadow prices generated in the model's solution.

Third, sources of greenhouse gases other than due to the use of hydrocarbons as fuels, as well as sources of potential amelioration of carbon emissions, are simply ignored.

Fourth, alternative energy technologies, not based on hydrocarbon fuels, are not considered.

While making a point of warning of the limitations of the demonstration, the authors believe that, at this relatively early stage of economic/environmental modeling, it is useful to present the method.

II. Fuel efficiency and carbon emissions

There are a number of sources of the "greenhouse effect" of which carbon emissions are only one. The use of hydrocarbon fuels, in turn, is only one among a number of sources of carbon emissions. It is, however, one of the most important sources, and has, therefore, been the focus of a good deal of attention.

Analysis of the economic consequences of both greenhouse effects and policies undertaken to prevent those effects are both at an early stage. Nonetheless it is transparently obvious that constraints on the use of fuels to reduce carbon emissions would, all other things equal, depress economic activity.[3] To ameliorate the consequences of assuming, "all other things equal," attention has been given to the potential for reduction in greenhouse gases through an increase in hydrocarbon fuel efficiency, i.e., the output/fuel input ratio. Whether that would offset the higher costs of substitute energy sources depends, of course, on the costs of obtaining higher fuel efficiency.

There have been a number of suggestive articles, which embody what might, at best, be described as a, "partial equilibrium approach," to this problem. The consequences of an improvement in hydrocarbon fuel efficiency are treated as if the only effects are the direct ones of a reduction in fuel requirements for any particular level of output.

This type of problem requires a "general equilibrium" analysis that takes into account both direct and indirect effects. The latter include: (1) the necessary changes in other input requirements, including capital requirements, in the process of economic growth and (2) changes in prices and the induced changes in composition of consumption and investment.

Improvements in fuel efficiency might come about in several ways: (1) through changes in engineering and maintenance practices that require adjustments that are virtually costless; (2) through increased investment in new plant and equipment that uses fuel more efficiently; (3) through technological changes that permit lower fuel input/output ratios with the same or lower amounts of capital and other inputs,.

It is reasonable to be skeptical with respect to the potential for improvements of the first type: costless increases in fuel efficiency. After all, if engineers and managers are profit maximizers, as conventionally assumed, it would, in general, be expected that any known adjustment that would reduce costs should have been exploited. If it has not been, the logic goes, the adjustment is not worth the effort.

On the other hand, there is a substantial literature that attests to the pervasive differences between "best practice" techniques and those that are in general use in production. Harvey Leibenstein brought this to the attention of the economics profession in a series of articles on, "X-inefficiency," so-called because it is not consistent with the conventional assumptions and methods of thoroughgoing profit maximization.[4]

Leibenstein associated such inefficiency with bureaucratic obstacles, inertia and a failure to respond to small incentives. In more contemporary language X-inefficiency might be "explained" in terms of information costs, transactions costs, and frictional adjustment costs, giving a broad definition to the terms so that they includes the effort necessary to change established patterns. In this sense, however, a reduction in X-inefficiency is not, in fact, costless, but requires, at the least, rearrangements that result in at least a temporary reduction in output, if not an increase in other inputs.

The potential for increasing hydrocarbon fuel efficiency through increased investment in plant and equipment deserves careful investigation. It should not be expected to be true, and is patently not the case, that even the most modern technologies are as fuel efficient as possible. A rational manager should maximize profits, which need not necessarily be the same objective as minimizing all costs and certainly not necessarily the same objective as minimizing fuel costs. However, as fuel costs increase, or constraints are imposed on carbon emissions through taxes or regulatory procedures, a shift to more fuel efficient technologies should be expected.

There are many uncritical enthusiasts for increased fuel efficiency. Yet the simple maxim, "when it pays, it will happen," is a good guideline. It need not express complacency, but rather may indicate the need for tax policy when markets do not fully reflect any externalities associated with fuel usage.

Even so, there are good reasons to think that the maxim might not have universal applicability. The X-inefficiency type of argument has already been mentioned. In addition, only if there are perfect capital markets will every project that can meet the going risk and return criteria be undertaken. The existence of credit rationing and other capital market imperfections will prevent that from happening.

The potential gains in fuel efficiency from technological changes have also been mentioned prominently as a source of reductions in carbon emissions. However, we should be cautious in making policies on this basis. We can wish for anything, but that will not make it so.

III. An economy-wide and intertemporal environmental model with alternative fuel efficiency possibilities

The model to be presented below has been used before by the authors to analyze the effects on economic growth of constraints on carbon emissions. It is a multisector, intertemporal optimizing model and, thus, is in the same spirit as the approach by Manne and Richels (1989). However, as a result of its restricted focus on a single country, it is more disaggregate and elaborate in a number of respects than would have been warranted in Manne and Richel's environmental modeling research.

The basic structure of the model is well-known from previous work by the authors and many others. The complete mathematical structure of the model is presented in an appendix and only those features that are particularly important for its present applica-

tion will be described here. The model was originally constructed for the analysis of energy policy in Egypt. It was adapted to the analysis of environmental issues since it is relatively detailed with respect to the sources and uses of energy, which, as noted above, is one of the primary sources of environmental offense.

For many purposes of environmental analysis, a country based analysis is the correct one. With some exceptions, as, for example, the Montreal agreement on the control of fluorocarbon emissions and regulation of the quality of the Rhine river, environmental policies are now national, rather than international. Economic policies, with only a few exceptions, are, likewise, national rather than international.

There are, moreover, differences among countries in their economic structures. These are important in the analysis of the effects of emissions constraints. In particular, the relative importance of the different productive sectors in developing countries is changing relatively rapidly. For example, in most of these countries, it should be expected that the weight of agriculture in the economy will decline relative to industry and that both production and consumption will become more energy intensive.

Nonetheless, some apologies are required for respecting national boundaries that are, for environmental purposes, often quite artificial. First, the local effects of some kinds of environmental pollution are the most important and averaging over a

larger area is misleading. Second, transnational effects may be not be confined only to border areas. With these apologies, a national model will be presented, but also with the belief that the methodology is generalizable and extendable.

The model used here has a 25 year time horizon, divided into five periods of five years each. This somewhat artificial pacing makes it possible to avoid a more detailed formulation of year-by-year interactions and dynamic processes while still generating a close temporal approximation of growth conditions. Results are reported for five, evenly-spaced years.

The economy is divided into ten sectors, six of which are non-energy sectors: agriculture, manufacturing, construction, transportation, services and non-competing imports. There are four energy sectors: crude oil, natural gas, petroleum products and electricity.

The economic variables determined by the model are investment, capital capacity and production by each sector, household consumption by sector, energy demand and supply, imports and exports and relative prices, all calculated for each of five evenly spaced, periods that are, in turn, five years apart.

As noted, the model focuses only on the generation of carbon emissions due to fuel use, although the methods are adaptable to other types of emissions associated with the use of any input or to the output of particular goods with specific technologies. The carbon emissions are calculated for each sector, as well as in total, for each period.

As an optimizing model, it maximizes an objective or welfare function which is the discounted sum of aggregate consumer utility over the model's horizon. The utility of the representative consumer in each time period is a weighted logarithmic sum over all goods of the difference between its consumption of each type of good and a parametrically fixed consumption level. Individual utility is multiplied by the projected population to obtain aggregate utility. This formulation is identical to simulating the market behavior of a representative consumer modeled as a linear expenditure system. It should be noted, in the present context, that environmental conditions do not enter the consumer's utility function directly. However, the consumer's choice of goods in the consumption basket will depend on relative prices and income levels, which are determined within the model, and those can be expected to be affected by environmental policies.

The usual material balance constraints, which require that the aggregate uses of output can be no greater than the aggregate availabilities, apply in each period. Availabilities depend on domestic production and imports, where the latter is feasible.

One of the most significant features of the model for the purposes of assessing the environmental impacts of economic activity is that, in general, production of each good can be carried out by alternative technologies, or, "activities," with different input patterns. The total output of each sector is the sum of the production from each of the technologies. Thus, there is the possibility of substitution among inputs in production

processes. The substitution is endogenously determined, in response to the relative prices of inputs and outputs, which are also determined endogenously. This is important for the analysis of environmental policies that either directly or indirectly affect the cost of inputs.

The alternative requirements for production in each sector are, with one exception, specified exogenously, as if they were taken from engineering specifications. The exception is in the demand for fuels, where, in effect, the BTU requirements per unit of output are specified, but the requirements can be met by using either natural gas or petroleum. Here, again, the choice will be made endogenously, depending on relative prices and any constraints that affect those prices.

Only three primary energy sources are distinguished: hydropower, crude oil and natural gas.[5] Production of each is constrained by availability. Crude oil is produced from petroleum reserves and the creation and use of these and of natural gas reserves is modeled to reflect the fact that the level of reserves is a function of the rate as well as the quantity of use of the resources and outputs to producers and consumers.

For the present purposes, increases in fuel efficiency are introduced in two alternative ways, as indicated briefly above. First, in a set of calculations, increases in fuel efficiency are incorporated in a costless manner simply by stipulating reduced fuel input requirements. Then increases in fuel efficiency are associated with increases in capital input requirements.

Production also requires labor inputs, whose unit requirements are also specified exogenously, but differently, for each technology or activity in each sector. There is an overall constraint on labor availability and, separately, a labor constraint in the agricultural sector intended to reflect limited rural-urban labor mobility and the tightness of the rural labor market over the past decade or so.

As is customary in such models, and different from the Jorgenson/Wilcoxen and Nordhaus models, capital is specific to each sector and, here, it is specific as well to the particular technology that it embodies. Capital formation in each period in each sector requires that investment be undertaken in the previous period. Depreciation rates are specified exogenously for the capital stock used by each technology in each period.

Foreign trade is confined to the tradable goods sectors: agriculture, manufacturing, transportation, other services, crude oil and petroleum products. As an approximate way of recognizing limited flexibility in the response of exports and imports to changes in relative prices, the rate of change of each of these is constrained, although within wide bounds.

The overall balance of payments constraint, that limits imports to what can be paid for from exports and foreign exchange resources, must also be met. Foreign borrowing is allowed, within moving upper bounds.

The problems of establishing initial and terminal conditions in a model of this sort are well-known. Here they are, largely,

finessed. The sectoral levels of investment in the initial period are constrained not to be greater than those actually achieved in 1987. The sectoral levels of investment in the terminal period are determined by the condition that they be adequate to sustain an exogenously specified rate of growth of output in the sector in the post terminal period. The terminal conditions create some anomalies in the final periods of the model's time horizon. Since that horizon is relatively long, these have only modest effects on the intermediate years.

With this description of the basic model in place it is possible now to turn to the features that deal with carbon emissions, which can, in fact, be described quickly. The quantity of carbon, V, that is generated by the use of a particular fuel, i, in a technology, k, in a particular sector, j, in period, t, is V_{ikjt}. So the total amount of carbon generated by the use of a particular fuel in the sector is obtained by summing over all technologies:

$$V_{ijt} = \sum_k V_{ikjt} \quad .$$

The total amount of carbon generated by the use of the particular fuel in all sectors is:

$$V_{it} = \sum_j V_{ijt} \quad .$$

The generation of carbon is related to the use of the particular fuel in the sector by a coefficient, v_{kijt}. I.e.,

$$V_{kijt} = v_{kijt} \, X_{kjt},$$

where the V_{ik}'s are understood to refer only to the fuel inputs.

The simple relationships are the conventional ones used in projecting the generation of environmental agents. Now, however,

that generation is a matter of endogenous determination in a complete model. So calculation of the generation of environmental agents is completely consistent with the calculation of the other features of the model, including its growth path.

The economic effects of carbon emissions constraints depends on the manner in which they are imposed. In a previous paper the authors investigated the relative effects of global as compared to sectoral emissions constraints.[6] It was not surprising to find that the latter had more depressing economic effects than the former. Attention will, therefore, be focused here on global or aggregate carbon emissions constraints. These take the form:

$$\sum_{i} v_{it} \leq \bar{v}_t \quad .$$

This type of restriction can be used to reflect the idea of "bubble" regulation. It is, essentially, regulating the total output of an environmental agent by a complex of industries so as to permit the individual industries to choose, themselves, the most efficient means of meeting the overall target.

This type of restriction will be applied with greater or lesser severity in various periods, in conjunction with different rates of fuel efficiency to investigate the trade-offs between reduction in the generation of carbon emissions and overall economic performance.

IV. Perspectives on the model

In this model, all adjustments are optimal, in terms of the maximization of the objective function. Moreover, they are made with perfect foresight over the model's time horizon. The im-

plicit assumption is that agents in the economy act efficiently to maximize their welfare with perfect foresight. A single solution of the model provides, therefore, what must be regarded as an optimistic projection of what can be achieved in terms of the maximand, given the endowments, the opportunities and constraints that are represented in its framework. While it is correct to question the reality of such optimism, the approach does meet the question often raised as to whether projected adjustments to policy are the most efficient ones.

In any case, a particular solution to the model is of less interest than the comparisons among solutions, which provide insights into problems and opportunities. This is particularly true when, as in the present application, the data represent only rough approximations. In the applications reported on here, the comparison will be between economic outcomes with and without carbon emission controls and with and without projected improvements in fuel efficiency. In all cases the solutions are dynamically efficient with respect to the objective function.

In the comparisons to be made, it is less clear that the results with respect to the effects of emission constraints should be interpreted as, "optimistic," since the basis for the comparison is also always an optimal result.

Even without actually solving the model we know what the effects of emissions constraints must be. If the constraints are binding, and it is expected that they will be, economic performance measured in terms of the objective function and the re-

lated output and income levels will suffer. Only on the assumption that there are costless ways of adjusting to the constraints could the results be different.

It is plausible for advanced countries that they should think of adjustments and sacrifices, if necessary, in their material living standards in order to gain the benefits, which are hard to quantify but which may be important, of lower absolute levels of emissions. It is just as plausible that developing countries, which are not close to the levels of living in industrialized countries, would resist a goal formulated in terms of absolute reductions in emissions.

If developing countries are going to be involved in the debate over reduction in carbon emissions, a more plausible basis for comparison is a reduction in emissions <u>relative to what they would have been, if the country had been following a growth path that was not constrained by emissions reduction</u>. This is the objective that is investigated here. It is, of course, different from targets related to the absolute levels of emissions at some original point in time.

V. Data base and parameterization

Data requirements of economy wide general equilibrium models of this nature are quite extensive since a complete, if aggregated, characterization of the economy is required.[7] The data needs can be classified into four broad categories: technological relationships, behavioral relationships, miscellaneous exogenous or predetermined variables, and initial conditions. The estima-

tion of these relationships and parameters is described in Blitzer, et al (1989). However, since substitution among energy inputs in production and consumption has a central role in this model, the methods used to provide the necessary data will be described briefly.

The principal source of primary data on the inter-industry structure of the Egyptian Economy is a 37 sector transactions matrix for 1983/84 obtained from CAPMAS.[8] The 37 sector matrix is aggregated into a ten sector classification, adjusted and updated to represent our base year transactions matrix of 1986/87. This transaction matrix provided much of the data for the implementation of the model.

The model is formulated to use one or more technologies to produce each good or service. The specific number of alternatives depends on sectoral characteristics. The alternative production technologies are divided in two categories. The first, encompasses the implicit technologies implied by the transactions matrix in 1986/87. The second category of technologies are the alternatives to the initial technology. In general, the alternatives allow for substitution between fuels, electricity, labor, and capital. The alternative technologies were derived using a small program which has as inputs: i) the initial technology, ii) the own-price elasticity of energy for the sector; and iii) the sectoral elasticities of substitution between labor and capital, between labor and energy, between capital and energy, and between electricity and fuels. The model takes the unit demand for fuels

as fixed for each technology; but this demand can be met by using either natural gas or petroleum products. At the same time, there are limits placed on the degree to which natural gas and petroleum products can be substituted for each other.

The methodology used in determining the parameters of the utility function in the maximand is based on a linear expenditure system of equations. The parameters of that function were first estimated econometrically, and then adjusted for consistency with the model's base year. The complete system of consumer demand functions has (2n-1) independent parameters. Since these equations are highly interrelated, a complete systems approach was used to econometrically estimate the parameters. The database for estimating these parameters was constructed by pooling cross-section family budget data which was available for two time periods, 1974/75 and 1980/81. Maximum likelihood estimates of the entire system were derived using the procedure of "seemingly unrelated regression."

As indicated above, the estimates of changes in fuel efficiency and the capital costs of retrofitting were based on an examination of the readily available literature. The estimates were chosen to reflect cautious optimism as to what is feasible. However, the authors would not attempt a vigorous defense of any of their guesses, but, as noted, represent them only as means of illustrating the methodology and the general nature of the results that might be expected.

VI. The effects on economic performance of restraints on carbon emissions

The first step is to obtain a "reference" solution to the

model, or base case. This is a solution with only the conventional assumptions with respect to the efficiency with which fuels are used and without any restrictions on carbon emissions. The next step is to impose a set of restrictions on carbon emissions, assuming also that these can be perfectly enforced. Since the model covers twenty-five years in five year time periods, the restrictions are also imposed over that period. The restrictions imposed are in the form of "umbrella" or "bubble" constraints, for the economy as a whole, rather than for individual sectors or even or individual establishments.

Table 1 presents the constraints as percentages of the total emissions generated in each period in the unconstrained emissions solution. The restrictions are stipulated for each future period as the model, as noted, is dynamic and extends over 25 years, capturing the reality of the need for forward-looking policy. As will be noticed the emission limits are, in a general sense, increasingly restrictive, over time and in successive solutions.

Table 1

Constraints on Total Carbon Emissions As Percentages of Total Emissions in Unconstrained Solution

	1987	1992	1997	2002	2007	2012
G1	100	0.95	0.90	0.85	0.80	0.70
G2	100	0.95	0.85	0.70	0.70	0.65
G3	100	0.90	0.80	0.65	0.65	0.65
G4	100	0.90	0.80	0.65	0.60	0.55
G5	100	0.85	0.75	0.60	0.55	0.45

The constraints are, in a general sense, increasingly restrictive over time and in successive solutions.

The solutions to the model contains a great deal of detail with respect to the sectoral patterns of inputs and outputs of the various sectors in successive periods. This detail is much too massive to be presented here and, for the present purposes, only certain aggregate features of the results are of interest. Table 2 presents data characterizing in a summary fashion the results of the solutions. For the base case and each of the alternative carbon emission scenarios Table 2 presents an index of carbon emissions that would be generated during the

Table 2

Characteristics of Alternative Solutions
With Different Levels and Patterns
of Carbon Emissions Constraints

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	94	89	86	85	81
Per Cent Change in Carbon Emissions		-6.28	-10.64	-14.45	-15.14	-18.88
Aggregate GDP Growth Per Cent	3.51	3.40	2.79	2.48	2.37	2.05
Per Cent Change in GDP Growth		-3.13	-20.51	-29.34	-32.48	-41.60
Per Cent Change in Welfare		-0.86	-2.27	-3.43	-4.04	-7.86

first 15 years and the growth rate of gross domestic product (GDP) over the same period. The percentage change in GDP growth in each scenario over the base case is also presented . Table 2 also presents the percentage change in consumer welfare over the base case as measured by the optimized objective function for each of the cases indicated in Table 1.

To repeat the initial warning, the data are too approximate to warrant reliance on the results in terms of the absolute levels. The percentage changes deserve more serious attention, although these too should be interpreted as more indicative of the range of possibilities than as predictions.

With this qualification in mind, perhaps the most interesting features of the results are the non-linear relations between reductions in carbon emissions, on the one hand, and reductions in measures of economic performance, on the other hand. The first 6.28 per cent reduction in carbon omissions in scenario G1 reduces GDP growth and the achievable utility only modestly. In scenario G2, which results in only an additional 4.36 per cent decline in carbon emissions as compared to G1, the decline in the growth rate of GDP is more than 6 times. Similar non-linearities are shown in the change in total discounted utility and in the successive scenarios. It may be recalled that in adjusting to the carbon emissions constraints, the model can take advantage of alternative technologies and sectoral shifts of resources, subject always to resource and balance of payments constraints.

<u>VII. Experiments with costless improvements in fuel efficiency</u>

The next set of experiments embody the analysis of the potential resulting from completely costless improvements in efficiency in the use of fuels in several sectors. Three alternative scenarios

Table 3

Alternative Percentage Reductions in Fuel Requirements
for
Natural Gas and Oil

Sectors	Scenario 1	Scenario 2	Scenario 3
Petroleum	0.05	0.05	0.05
Electricity	0.04	0.04	0.04
Manufacturing	0.05	0.10	0.15
Construction	0.05	0.05	0.05
Transport	0.05	0.10	0.15

of this type were tried with the changes shown in Table 3.

It might be objected that these are relatively modest improvements in efficiency as compared to the substantial changes that can be foreseen in the future. Most discussion of such improvements involve capital costs for new equipment.

Table 4 indicates the consequences of such efficiency improvements when the model adjusts to the set of carbon emissions constraints shown in Table 1. Part of the adjustments shown in Table 4 result simply from the availabilities of the costless, more fuel efficient technologies. Those would be used in an optimizing model, whether or not there were carbon emissions constraints and would result in increased output and welfare. It is possible to see this happening in the background, for example, in scenario G1, in Table 4. In this case there is an additional 2.41 per cent reduction in carbon emissions (which is evident from the percent change in carbon emissions row), as compared to the same scenario in Table 2, but a very small reduction in welfare.

The adjustments are uneven, however, as among the scenarios. In scenario G3 in Table 4, for example the reduction in carbon emssions is .63 percent more than in the same scenario in Table 2.

Because of the improvements in fuel efficiency, the required reductions in carbon emissions always have a less depressing effect on economic performance than shown in Table 2. In scenario G1 in Table 4, there is an actual improvement in economic performance because of the provision of new, costless and fuel efficient technologies. Nonetheless, as the carbon emissions constraints become more restrictive, economic performance declines substantially, though never by so much as shown in Table 2. There are reductions in consumer welfare in all cases, but, again, less so than if the improvements in energy efficiency were not available. This indicates that, although real economic activity is affected less than before by the carbon emissions constraints, the results are less satisfying in terms of the optimized utility function.

Table 4

Characteristics of Solutions
With Costless Improvements in Fuel Efficiency of Scenario 1
in The Adjustment to Carbon Emissions Constraints

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	91	87	85	84	79
Per Cent Change in Carbon Emissions		-8.69	-13.15	-15.08	-15.81	-21.18
Aggregate GDP Growth Per Cent	3.51	3.67	3.08	2.85	2.82	2.31
Per Cent Change in GDP Growth		4.59	-12.34	-18.75	-19.77	-34.13
Per Cent Change in Welfare		-0.37	-2.00	-2.71	-3.30	-7.36

Table 5 presents the solutions corresponding to the alternative

sets of carbon emissions constraints and the costless reductions in fuel requirements presented in scenario 2 in Table 3. In this case, the improvements in fuel efficiency are substantial and GDP growth rates are always higher than those represented in Table 2, and the decline in the objective function values are also less marked compared to that of Table 2.

Table 5

Characteristics of Solutions
With Costless Improvements in Fuel Efficiency of Scenario 2
in The Adjustment to Carbon Emissions Constraints

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	90	86	84	83	78
Per Cent Change in Carbon Emissions		-10.13	-14.24	-16.14	-17.26	-22.37
Aggregate GDP Growth Per Cent	3.51	3.71	3.11	2.88	2.83	2.33
Per Cent Change in GDP Growth		5.75	-11.40	-18.06	-19.34	-33.70
Per Cent Change in Welfare		-0.26	-1.87	-2.59	-3.19	-7.17

With even more substantial, and still costless, improvements in fuel efficiency, overall performance continues to improve, relative to the cases without such improvements. Relatively speaking, the improvements are much less substantial in the case with the most restrictive carbon emissions constraints, as compared to the other cases.

This feature of the results are shown again in Table 6, which presents results of the solution with the costless reductions in fuel requirements shown in scenario 3 in Table 3. In this case, as

Table 6

Characteristics of Solutions
With Costless Improvements in Fuel Efficiency of Scenario 3
in The Adjustment to Carbon Emissions Constraints

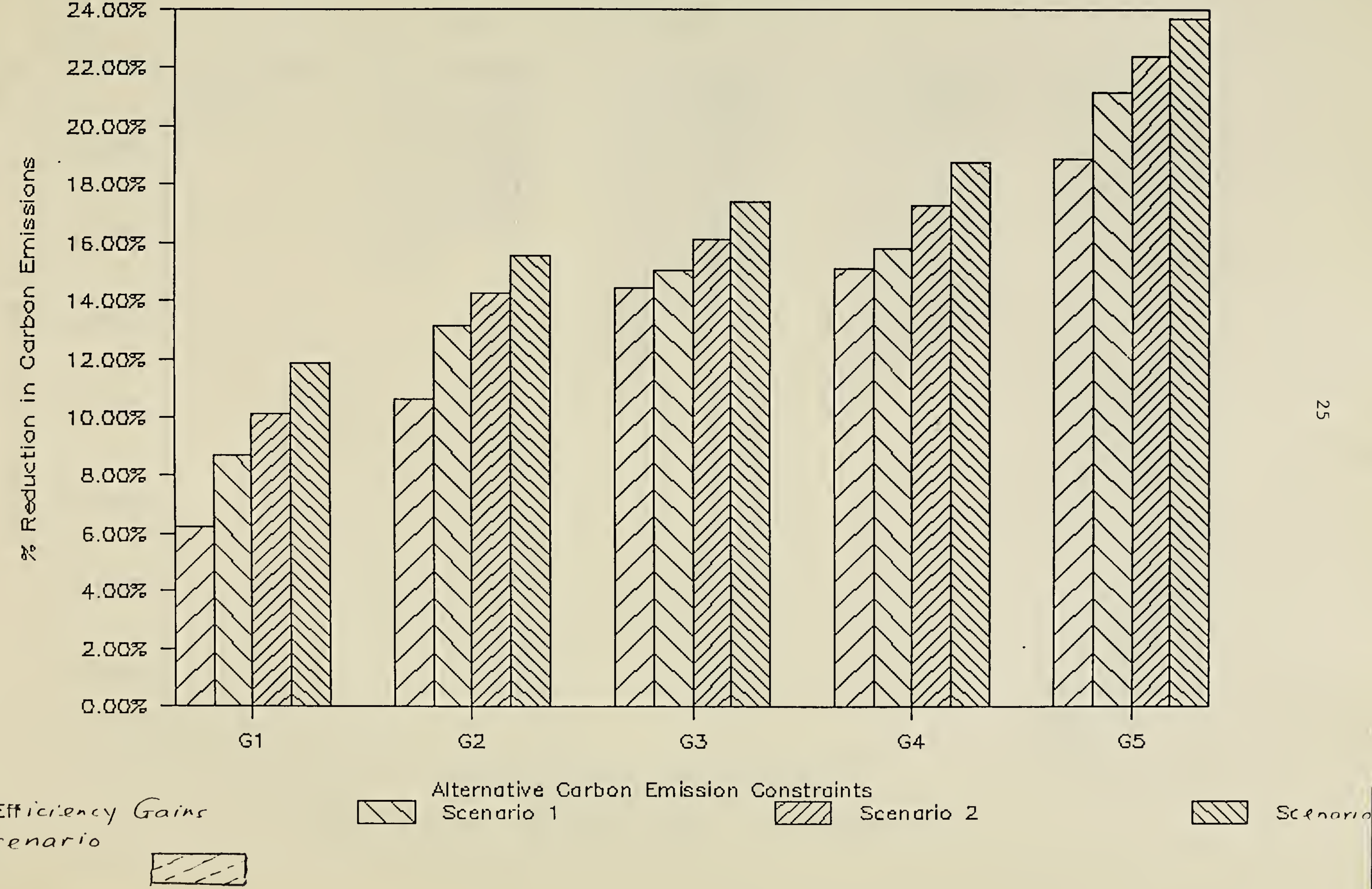
Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	88	84	83	81	76
Per Cent Change in Carbon Emissions		-11.84	-15.53	-17.38	-18.79	-23.67
Aggregate GDP Growth Per Cent	3.51	3.76	3.15	2.90	2.86	2.36
Per Cent Change in GDP Growth		7.07	-10.31	-17.35	-18.40	-32.79
Per Cent Change in Welfare		-0.13	-1.74	-2.45	-3.06	-6.98

in the previous two cases, improvements in fuel efficiency make it much easier for the model adjust to the carbon emissions constraints. Yet the degree of satisfaction of consumer utility continues to fall below the maintenance of economic activity. And, in this case also, the most binding of the carbon emissions constraints continues to have extremely negative effects on the economy.

Charts 1 and 2 summarize the results shown in Tables 2,4,5 and 6. The charts help make the point that linear extrapolations would

Per Cent Reduction in Carbon Emissions

Costless Efficiency Change Scenarios



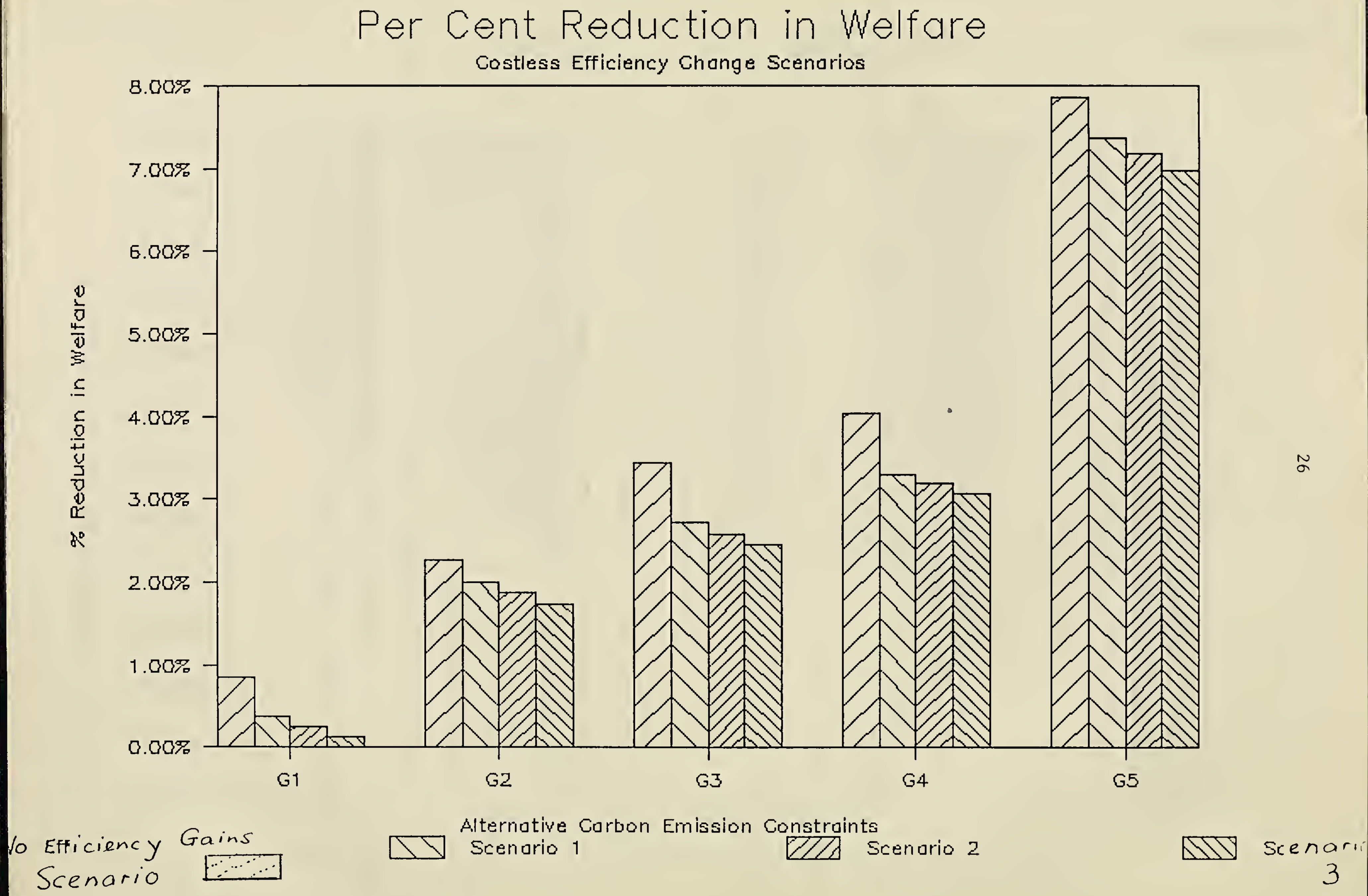

Per Cent Reduction in Welfare
Costless Efficiency Change Scenarios
% Reduction in Welfare
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
G1
G2
G3
G4
G5
Alternative Carbon Emission Constraints
No Efficiency Gains Scenario
Scenario 1
Scenario 2
Scenario 3

Table 7
Alternative Retrofit Scenarios With Improvements in Fuel Efficiency

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Reduction in fuel coefficient in manufacturing	0.2	0.3	0.0	0.2
Reduction in fuel coefficient in transport	0.0	0.0	0.5	0.5
Payback period in years in manufac-turing	2.5	5.0		2.5
Reduction in incremental capital output/ratio in transport			10 %	10 %

These scenarios were used in alternative model solutions for each set of carbon emission constraints. Table 8 presents the results for Scenario 1 in Table 7 and the alternative emissions constraints in Table 1.

Table 8

Characteristics of Solutions With Improvements in Fuel Efficiency That Require The Additional Capital of Scenario 1, Table 7

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	91	87	85	83	57
Per Cent Change in Carbon Emissions		- 9.49	-12.81	-15.02	-16.51	-43.05
Aggregate GDP Growth Per Cent	3.51	3.67	3.03	2.80	2.76	2.30
Per Cent Change in GDP Growth		4.56	-13.56	-20.11	-21.28	-34.50
Per Cent Change in Welfare		-0.34	-2.01	-2.75	-3.42	-8.01

the changes in overall economic performance are quite modest, except, again, in the G5 case.

The third scenario in this series involves improvements in fuel efficiency in the transport sector, achieved through increases in capital requirements per unit of output. The overall results from this experiment are shown in Table 10. The striking feature of these results are that the substantial improvement in fuel

Table 9

Characteristics of Solutions With Improvements in Fuel Efficiency That Require The Additional Capital of Scenario 2, Table 7

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	89	86	84	82	55
Per Cent Change in Carbon Emissions		-11.39	-14.29	-16.44	-18.16	-45.14
Aggregate GDP Growth Per Cent	3.51	3.70	3.03	2.79	2.75	2.13
Per Cent Change in GDP Growth		5.27	-13.62	-20.51	-21.71	-39.32
Per Cent Change in Welfare		-0.31	-2.00	-2.75	-3.46	-8.69

efficiency in transport has larger effects on economic growth in all the cases, as compared to not having such improvements. However, the effects on economic welfare, as measured by the objective function, are rather modest, except in the G5 scenario. Presumably this reflects the fact that, in the Egyptian economy there is relatively little use of private automobiles for transport. Thus the cost of the use of fuel for transport enters the objective only indirectly, through the cost of non-transport goods and services.

The comparisons are becoming more than a little awkward. However, they may be simplified by reference to Table 2. It is clear that exploitation of the option of retrofitting capital in adjusting to carbon emissions constraints improves the overall economic performance of the economy. Nonetheless the adjustments to the carbon emissions constraints generally results in lower real output and reductions in economic welfare, with the former being larger than the latter. The exceptional case is G5, which has the most restrictive carbon emissions constraints. While fitting the general pattern the reductions in carbon emissions, growth and welfare are all much larger than in previous trials. It will be recalled that G5 is the most restrictive set of carbon emissions constraints. In this trial, when new, more capital intensive, and less fuel intensive, methods are forced on the system in order to reduce carbon emissions, there is very little opportunity left for growth. The relatively large reductions in carbon emissions, larger than required by the constraints, are the result of much lower levels of economic performance. This demonstrates one possibility of which there have been warnings: that required reductions in carbon emissions, even with new technologies, may substantially depress economic growth. Nonetheless the performance of the economy is still better than if the technological improvements in fuel efficiency had not been employed.

Scenario 2 in Table 7 is implemented next, again with the alternative sets of carbon emissions constraints. The results are shown in Table 9. Although the fuel coefficients are reduced by fifty per cent more in this scenario as compared to the previous one

The effects on carbon emissions and aggregate welfare in the solutions for all the scenarios outlined in Table 7 are shown in Charts 3 and 4. Comparisons with Charts 1 and 2 provide some interesting insights. It is clear that the improvements in fuel efficiency will reduce carbon emissions in both cases. However, comparison of Charts 2 and 4 suggests that forcing changes in fuel use that are not required by the carbon emissions policy can lead to larger reductions in consumer welfare than would otherwise take place.

Table 11

Characteristics of Solutions With Improvements in Fuel Efficiency That Require The Additional Capital of Scenario 4, Table 7

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	81	79	77	76	72
Per Cent Change in Carbon Emissions		-14.10	-21.19	-22.76	-24.28	-28.11
Aggregate GDP Growth Per Cent	3.51	3.78	3.14	2.92	2.87	2.42
Per Cent Change in GDP Growth		7.69	-10.54	-16.81	-18.23	-31.05
Per Cent Change in Welfare		-0.25	-1.79	-2.45	-3.03	-6.36

IX. Conclusions

It would be misplaced concreteness to claim much in the way of substantive insight for the results presented here. These results are intended to represent the potential of a methodology.

table

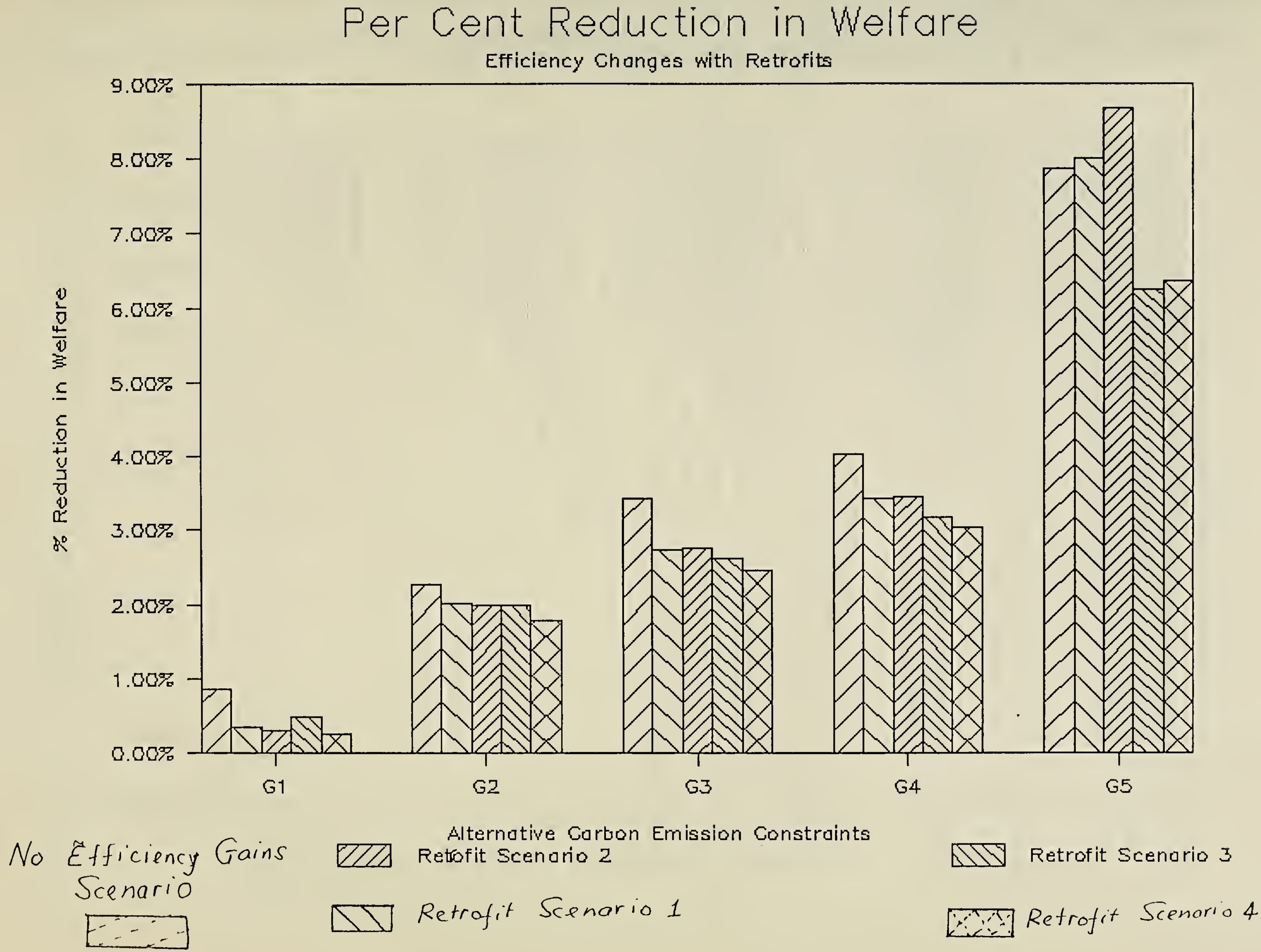
It is interesting to compare these results with those for the previous two scenarios, in which improvements in fuel efficiency were confined to the manufacturing sector. The fuel efficiency improvement in the transport sector was much larger than in manufacturing. However, the differential effects were relatively modest, except in the case of the most restrictive carbon emissions constraints.

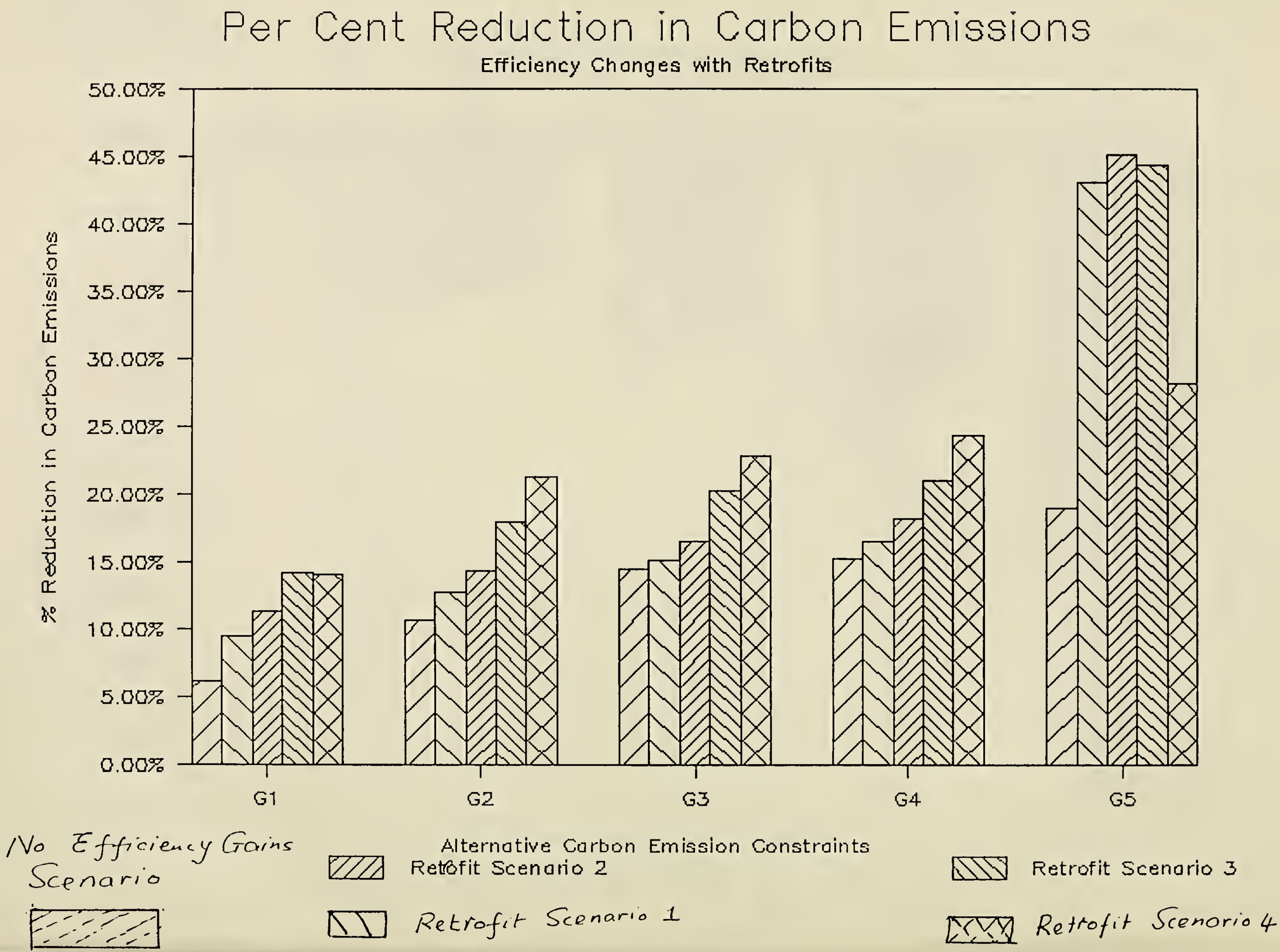
Table 10

Characteristics of Solutions With Improvements in Fuel Efficiency That Require The Additional Capital of Scenario 3, Table 7

Global Carbon Constraint Scenarios	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	100	86	82	80	79	56
Per Cent Change in Carbon Emissions		-14.12	-17.85	-20.27	-21.02	-44.41
Aggregate GDP Growth Per Cent	3.51	3.72	3.13	2.94	2.87	2.42
Per Cent Change in GDP Growth		5.95	-10.77	-16.27	-18.29	-31.20
Per Cent Change in Welfare		-0.49	-1.99	-2.63	-3.16	-6.26

Finally, in Table 11, results are shown for Scenario 4 of Table 7, which combines Scenarios 1 and 3 of that Table.


Per Cent Reduction in Welfare
Efficiency Changes with Retrofits
% Reduction in Welfare
9.00%
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
G1
G2
G3
G4
G5
Alternative Carbon Emission Constraints
No Efficiency Gains Scenario
Retrofit Scenario 2
Retrofit Scenario 3
Retrofit Scenario 1
Retrofit Scenario 4


Per Cent Reduction in Carbon Emissions
Efficiency Changes with Retrofits
% Reduction in Carbon Emissions
50.00%
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
G1
G2
G3
G4
G5
Alternative Carbon Emission Constraints
No Efficiency Gains Scenario
Retrofit Scenario 2
Retrofit Scenario 3
Retrofit Scenario 1
Retrofit Scenario 4

APPENDIX

Table 4
Parameters and Exogenous Variables

a_i	Maximum annual rate of depletion of hydrocarbon resource i (oil or natural gas)
$a_{i.j.k}$	Input of good i per unit of production of good j using technology k
$a_{fuel.j.k}$	Input fuel per unit of production of good j using technology k
$a_{gas.j.k}$	Input of natural gas per unit of production of good j using technology k
$a_{pet.j.k}$	Input of petroleum products per unit of production of good j using technology k
$b_{i.j.k}$	Proportion of capital good i in the capital required to produce good i using technology k
$d_{i.k}$	Five-year rate of depreciation of capital for production of good i using technology k
e_i	Maximum rate of increase of exports of good i between two periods
i_t	interest rate of foreign debt in year t
g_i	Minimal post-terminal growth rate for sector i
$f_{i.k}$	capacity conversion factor for capitol producing good i using technology k
$ICOR_{i.k}$	Incremental capital-output ratio for production of good i using technology k
$l_{i.k}$	Demand for labor per unit of production of good i using technology k
$l_{agr.k}$	Demand for labor per unit of agricultural production using technology k
m_i	Maximum rate of fall of imports of good i between two periods
q_i	Conversion factor for hydrocarbon resource i (oil or natural gas)
$s_{j.k}$	Maximum share of natural gas in meeting fuel demand of producing good j using technology k
β_i	Elasticity parameter for consumption good i
γ_i	Intercept parameter for consumption good i
ρ	Utility discount rate between periods
$\overline{B}_t$	Maximum net foreign borrowing in year t
$\overline{G}_{i.t}$	Public consumption of good i in year t
I_{1987}	Aggregate imported in 1987
$\overline{L}_t$	Total supply of labor in year t
$\overline{L}_{agr.t}$	Supply of agricultural labor in year t
$\overline{N}_t$	Population in year t
$\overline{\Delta R}_{i.t+1}$	Discoveries of resource i (oil or natural gas) between year t and year t+1
$\overline{T}_t$	Other foreign exchange transfers in year t
$\overline{FP}_t$	Foreign firms' profit remittances in year t
$\overline{W}_t$	Workers' remittances in year t
$p^e_{i.t}$	world price of exports at good i in year t
$p^m_{i.t}$	world price of imports at good i in year t

The substantive results which do exist originate in the comparison of the alternative scenarios and cases. The demonstration of nonlinearity in the economic impact of carbon emission constraints appears to the authors to be a robust outcome. There are no features of the model that would necessitate such an effect.

The subtleties in the adjustments to changes in efficiency and emission constraints and the differences in the adjustments depending on the strictness of the constraints appears to be additional robust results. They warn against simplistic diagnoses and policy prescriptions.

While complex by comparison to many economic models, this model is still a relatively simple depiction of an economy. Nonetheless its complexity is sufficient to provide an important warning: carbon emissions constraints, depending on their severity, can have far-reaching and profound economic effects. To convey any other message would be playing Polyanna.

Table 5

Endogenous Variables

B_t	Net foreign borrowing in year t
$C_{i,t}$	Private consumption of good i in year t
D_t	Foreign debt in year t
$E_{i,t}$	Exports of good i in year t
$I_{i,t}$	Investment demand for good i in year t
$I_{i,j,k,t}$	Demand for investment good i by sector j, technology k, in year t
$K_{i,k,t}$	Installed capacity in year t to produce good i using technology k
$\Delta K_{i,k,t}$	New capacity to produce good i using technology k,first available in year t
$M_{i,t}$	Imports of good i in year t
$P_{i,t}$	Shadow price of good i in year t
$R_{i,t}$	Reserves of hydrocarbon i (oil or natural gas) in year t
$U(C_t)$	Utility of per capita consumption in year t
W	Total discounted utility; the maximand
$X_{i,t}$	Gross domestic output of good i in year t
$X_{i,k,t}$	Gross output of good i, produced using technology k,in year t
$Z_{i,t}$	Intermediate deliveries of good i in year t

V_{it}	Total amount of carbon generated by the use of a particular fuel, i, in period, t
V_{ijt}	Total amount of carbon generated by the use of a particular fuel, i, in sector j, in period, t
V_{ikjt}	Amount of carbon generated by the use of a fuel, i, using technology k, in sector j, in period, t
V_{ict}	Amount of carbon generated by the use of a particular fuel, i, in consumption in period, t
v_{ikjt}	Quantity of carbon emission <u>per unit</u> use of particular fuel, i, using technology k, in sector j, in period, t
v_{ict}	Quantity of carbon emission per unit use of a fuel, i, in consumption in period, t

$\bar{V}_t$ Maximum amount of carbon that may be generated in period, t

$\bar{V}_{jt}$ Maximum amount of carbon that may be generated, by sector j, in period, t

$\bar{V}_{ikjt}$ Maximum amount of carbon that may be generated, by the use of a particular fuel i, using technology k, in sector j, in period, t

$$R_{i,t+1} = R_{i,t} + \overline{\Delta R}_{i,t+1} - 2.5(X_{i,t+1} + X_{i,t})q_i \tag{15}$$

$$D_{t+1} = D_t + 2.5(B_{t+1} + B_t) \tag{16}$$

Investment Demand

$$I_{i,t} = \sum_j \sum_k I_{i,j,k,t} \tag{17}$$

$$I_{i,j,k,t} = b_{i,j,k}\, ICOR_{j,k}\, \Delta K_{j,k,t+1} \tag{18}$$

$$\sum_i I_{i,1987} \le \bar{I}_{1987} \tag{19}$$

$$\sum_k K_{i,k,2017} \ge (1+\bar{g}_i) \sum_k K_{i,k,2012} \tag{20}$$

Carbon Emissions

$$V_{ijt} = \sum_k V_{ikjt} \tag{21}$$

$$V_{it} = \sum_j V_{ijt} \tag{22}$$

$$V_{ict} = v_{ict} C_{it} \tag{23}$$

$$V_{kijt} = v_{kijt}\, X_{kjt} \tag{24}$$

$$V_{ijkt} \le \bar{V}_{ijkt} \tag{25}$$

$$V_{it} \le \bar{V}_{it} \tag{26}$$

$$\sum_i (V_{it} + V_{ict}) \le \bar{V}_t \tag{27}$$

MODEL

Accounting Identities

$$X_{i,t} + M_{i,t} = Z_{i,t} + C_{i,t} + \overline{G}_{i,t} + I_{i,t} + E_{i,t} \tag{1}$$

$$X_{i,t} = \sum_{k} X_{i,k,t} \tag{2}$$

$$Z_{i,t} = \sum_{j} \sum_{k} a_{i,j,k} X_{j,k,t} \tag{3}$$

$$\sum_{i} P^{e}_{i,t} E_{i,t} + \overline{W}_{t} + \overline{T}_{t} + B_{t} = \sum_{i} P^{m}_{i,t} M_{i,t} + i_{t} D_{t} + \overline{FP}_{t} \tag{4}$$

Technology and Production Constraints

$$a_{gas,j,k} + a_{pet,j,k} = a_{fuel,j,k} \tag{5}$$

$$a_{gas,j,k} \leq s_{j,k}\, a_{fuel,j,k} \tag{6}$$

$$\sum_{i} \sum_{k} l_{i,k} X_{i,k,t} \leq \overline{L}_{t} \tag{7}$$

$$\sum_{k} l_{agr,k} X_{agr,k,t} \leq \overline{L}_{agr,t} \tag{8}$$

$$X_{i,k,t} \leq K_{i,k,t} \tag{9}$$

$$q_{i} X_{i,t} \leq a_{i} R_{i,t} \tag{10}$$

Balance of Payments and Trade Constraints

$$B_{t} \leq \overline{B}_{t} \tag{11}$$

$$M_{i,t} \geq (1-m_{i})\, M_{i,t-1} \tag{12}$$

$$E_{i,t} \leq (1+e_{i})\, E_{i,t-1} \tag{13}$$

Dynamic Linkages

$$K_{i,k,t+1} = K_{i,k,t}(1-d_{i,k}) + f_{i,k}\, \Delta K_{i,k,t} \tag{14}$$

1 The focus of the paper should not be interpreted as a judgment on the dangers, actual or incipient, of a "greenhouse" effect, due to carbon emissions, on which no position is taken here. It is, rather, an exploration of the consequences of some of the policies proposed in anticipation of the problem.
2 See R. Ayres, (1989).
3 Several attempts have been made to quantify these effects including D. Jorgenson and P. J. Wilcoxen, (1989), A. Manne and R. Richels (1989), W. Nordhaus, (1989), and C. Blitzer, et al,(1989).
4 See H. Leibenstein, (1966), (1987).
5 It should be recalled that the purpose in presenting the model is primarily methodological. The omission of coal as a primary energy source would, of course, be quite wrong for most countries, although correct in the case of Egypt.
6 Blitzer, et al, (1989).
7 See Blitzer, et al, (1989).
8 Central Agency for Public Mobilization and Statistics (CAPMAS).

Objective Function

$$W = \sum_{t} \left(\frac{1}{1+\rho}\right)^{t} N_{t}\, U(C_{t}) \tag{28}$$

$$U(C_{t}) = \sum_{i} \beta_{i} \ln \left(\frac{C_{i,t}}{\bar{N}_{t}} - \gamma_{i}\right) \tag{29}$$

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